An Investigation into the Constraints of Reactive Power Output in Contemporary Photovoltaic Inverters

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Abstract:

The rise in photovoltaic (PV) system adoption has suggested incorporating intelligent functionalities into PV inverters to replicate the grid support functions seen in traditional power plants. One such function involves using PV inverters for static and dynamic reactive power injection for grid voltage stabilization. Different control strategies for managing reactive power have been explored, showcasing precise and rapid control capabilities. However, discussions on the limitations of reactive power output still need to be completed. Variations in semiconductor behavior between actual and reactive power injection result in differing output capacities for reactive power. This investigation compares the maximum reactive power capabilities of three standard PV inverter designs: 2-level full bridge, 3-level Neutral Point Clamped (NPC), and T-type Neutral Point Clamped (TNPC). The study notes that PV inverters generally exhibit greater reactive power capacity than absolute power. This attribute is advantageous for improving intelligent PV inverters' grid voltage support function. Consequently, based on these findings, a novel model is proposed, which constrains apparent power to aid the reactive power dispatch controller.

Keywords*:* *Photovoltaic (PV) systems, PV inverters, Reactive power and Real power*

Introduction

The growing adoption of photovoltaic (PV) generation is fueled by lower costs and supportive governmental policies. Over the past decade, global PV capacity has surged from 5.1 GW to 227 GW, with expectations of further expansion (REN21, 2016). However, PV inverters that introduce high levels of active power during periods of low demand can lead to transformer overloads or excessively high grid voltages (Su et al., 2014). This voltage increase poses a significant challenge to integrating PV into low-voltage (LV) distribution networks. On the other hand, interruptions in PV generation on cloudy days can cause voltage drops. Conventional voltage regulation tools like secondary LV online tap changers (OLTC), voltage regulators, and switched capacitors often have limited responsiveness due to inherent limitations (Godwin et al., 2013). While solutions such as upgrading distribution conductors and incorporating energy storage devices are effective, they also come with considerable costs.

A pragmatic and innovative approach involves transitioning the control and functionality of PV inverters from merely generating PV power to operating as four-quadrant converters capable of both active and reactive power. This shift towards utilizing the inverter as a distributed reactive power source has garnered significant interest from utility companies. Different control objectives are being explored to exchange reactive power with the grid in a decentralized manner and maintain a steady voltage profile (Kabiri et al., 2014). Moreover, there is an emphasis on minimizing feeder losses, prolonging inverter lifespan, and managing voltage regulation expenses. Although the costs of PV inverters are usually justified by their ability to inject active power, integrating reactive power capabilities provides an economical means to achieve substantial distributed compensation along a feeder. However, the extended use of a PV inverter for reactive power compensation, whether during the day or night, may diminish its operational lifespan (Varma et al., 2015).

Additionally, since injecting reactive power leads to extra power losses, a robust business strategy must be in place to compensate PV system owners. From the utility's standpoint, determining the allowable amount of reactive power that PV inverters can inject or absorb is another crucial consideration (Yang et al., 2014). Hence, assessing the reactive power capacity and the associated power losses is vital before establishing a viable business case for reactive-capable PV inverters. The primary function of traditional PV inverters is to inject active power into the grid only, operating under a unit power factor. The maximum active power value, Pmax, corresponds to the inverter's nameplate value and is also considered the apparent power limit.

Consequently, the capability of PV inverters is illustrated in Fig.1, where the maximum reactive power value, Qmax1, equals Pmax. Following the relationship among active power P, reactive power Q, and apparent power S, the inverter must operate under the condition where P and Q satisfy Equation (1), where Srated is also equal to Pmax. This indicates that the available operational range for traditional PV inverters is depicted as the semi-circle in Fig.1, the PV inverter capability curve.

$$(P)^2 + (Q)^2 \le (S_{rated}) \qquad (1)$$

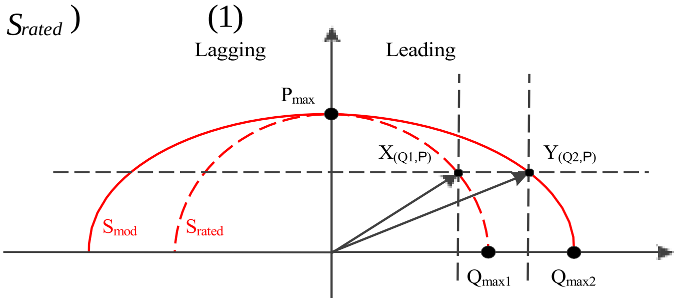
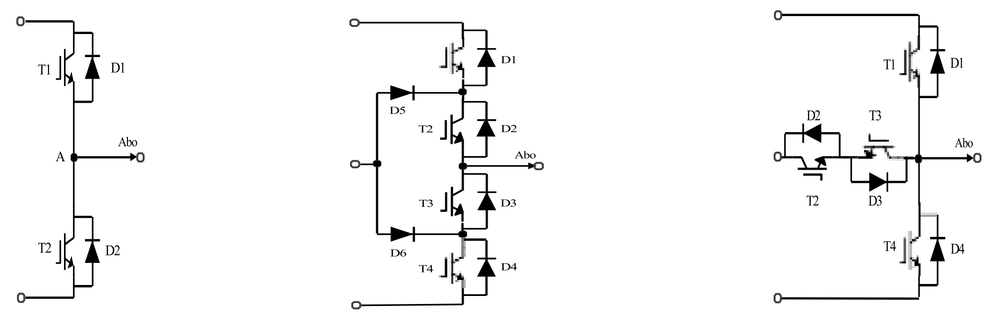


Fig.1. Capability curve for PV inverter

This adjustment is necessary because the maximum reactive power value, Qmax2, exceeds that of Qmax1. Various factors contribute to this difference, such as the inverter's topology, modulation techniques, and the type of power semiconductor devices used. When the inverter generates reactive power, the power loss associated with the semiconductor devices deviates from conditions where the power factor is unity. The maximum apparent power limit of the converter depends on the highest operating temperature among all semiconductor devices. If losses are evenly distributed across each device, the inverter will reach its physical capacity limit at a significantly higher rating. This research focuses on three common three-phase PV inverter topologies: the 2-level, 3-level Neutral Point Clamped (NPC), and 3-3-level T-type Neutral Point Clamped (TNPC) topologies. The goal is to analyze their power losses and determine the maximum reactive power capability, Qmax2. Based on this analysis, a revised model for apparent power constraint is proposed to optimize the utilization of PV inverters across different power factor scenarios. The comparison among these topologies also considers their output capacity and cost implications. The paper concludes with a simulation demonstrating the reactive power capability of a single-phase PV inverter throughout the day to highlight these research findings.

Operational Principle of Pv Inverter, Thermal Model and Loss Calculation

The primary limitation of a PV inverter's output capability stems from its power devices' thermal constraints. As power is lost, the temperature of these devices increases, with each technology having a maximum temperature limit that defines the physical restriction on the inverter's power handling capacity once the cooling system is established. The operational principles of three inverters—2-level, 3-level NPC, and 3-level T-type TNPC topologies—are examined to determine power loss. Each topology, depicted in Figure 2 for one phase of each, differs in the number and rating of devices and the modulation scheme, resulting in varying power device losses. To accurately calculate these losses, an analysis of inverter operation is necessary. Traditional PV inverters usually function at unity power factor, meaning they supply only active power to the grid. However, the inverter needs bidirectional power flow capability to inject reactive power, typically determined by its chosen design and modulation. Figure 3 illustrates how the inverter operates under varying power factor conditions from unity. It shows two states with a phase shift between voltage and current: P+ indicates inverter operation, while P- indicates rectifier operation. Understanding the power device involves examining its switching state and the reactive power of the conduction circuit during different operational scenarios. The primary limitation on a PV inverter's output capability comes from its power devices' thermal constraints.



(a) 2-level (b) NPC (c) TNPC

T1

Fig.2.One arm of three typical PV inverters

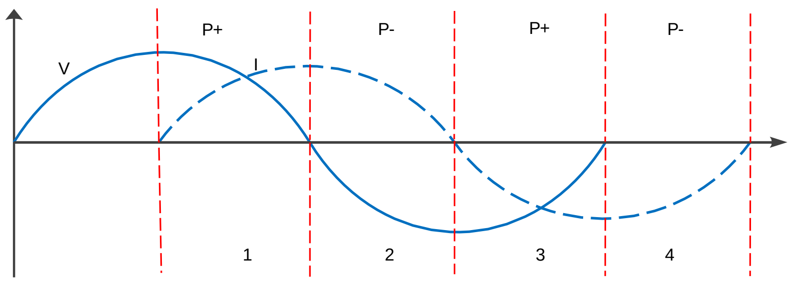


Fig.3. Inverter Operating area

In a 2-level converter, T1 and T2 conduct during inverter operation, while D1 and D2 conduct during rectifier operation. For the 3-level Neutral Point Clamped (NPC) topology, T1, T2, T3, and T4 conduct during inverter operation, and D1, D2, D3, and D4 conduct during rectifier operation. In the 3-level T-type Neutral Point Clamped (TNPC) topology, T1 and T4 are conducted during inverter operation, and D1 and D4 are conducted during rectifier operation. Analyzing their switching states reveals that during rectifier operation, the loss and thermal stress shift from the transistor to the diode. Additionally, diodes typically have more minor reverse recovery losses than transistor switching losses, allowing these inverters to handle more reactive power injection or absorption than active power.

Specific equations are applied when calculating the power loss of the primary power devices used in PV inverters, typically silicon IGBTs and diodes. For IGBTs, the total power loss (PT) encompasses both conduction loss (PCT) and switching loss (PswT), as outlined in Equation (2). In this Equation, UCE0 represents the conduction voltage drop, rC signifies the collector-emitter on-state resistance, and Icav and Icrms denote the average and RMS current values, respectively. Switching losses result from switching energies, which include the summation of turn-on loss (EonT) and turn-off loss (EoffT) multiplied by the switching frequency (fsw).

$$P_T = P_{CT} + P_{swT} \qquad (2)$$

The conduction loss of a diode is computed similarly to that of IGBTs. However, unlike IGBTs, diodes do not have turn-on losses. Their turn-off energy primarily comprises the reverse-recovery energy, denoted as EoffD. The total loss of a diode is calculated as follows:

$$P_D = P_{CD} + P_{swD} \qquad (3)$$

The power losses in both the IGBT and diode are dissipated through their respective junction-to-case thermal resistances (Rth(j-c)IGBT for IGBT and Rth(j-c)D for the diode). This dissipation causes the junction temperature (TjIGBT for IGBT and TjD for the diode) to be above the casing temperature. The cumulative power losses from these devices contribute to a temperature rise of both the case (Tc) and the heat sink (Th) above the ambient temperature (Ta), facilitated by the case-to-heat sink thermal resistance (Rth(c-h)) and heat sink-to-ambient thermal resistance (Rth(h-a)). The junction temperature rise of the IGBT and diode over the case temperature is determined using equations (4) and (5):

$$T_{jIGBT} = T_a + R_{th(j-c)IGBT} \cdot P_T \qquad (4)$$

$$T_{jD} = T_a + R_{th(j-c)D} \cdot P_D \qquad (5)$$

The power rating of the PV inverter is limited by the device with the highest temperature, as it sets the overall thermal constraints. To maintain the temperature rise within a specified limit, Trlim, the maximum permissible power losses on the IGBT and diodes are represented as PTmax and PDmax, respectively. They are determined using equations (6) and (7):

$$P_{T\max} = T_{r\lim} / R_{th(j-c)IGBT} \qquad (7)$$

$$P_{D\max} = T_{r\lim} / R_{th(j-c)D} \qquad (8)$$

Three Inverters' Output Power Capabilities

To determine the maximum power handling capacity of each inverter for active (P) or reactive (Q) power injection, we present the results of device loss calculations for the three topologies. The thermal performance limits of each device within the topology establish constraints for both active and reactive power capabilities. The system parameters utilized in these calculations are listed below:

Table I. Calculation of Loss Parameters

Parameters	Values	Parameter	Values
DC link voltage	800V	***IGBT current rating***	50A
AC line-line voltage	480V	***IGBT voltage rating***	650/ 1200V
AC frequency	60Hz	***Maximum junction temperature***	135 C
Switching frequency	16kHz	***Heat sink temperature***	100 C

You can consult the datasheet datasheets for NGTB50N65FL2WG and NGTB50N120FL2WG for more information on specific IGBT parameters. We have selected certain IGBT specifications based on the characteristics of each topology:

- For the 2-level inverter, a 50A/1200V IGBT is being used.
- In the NPC inverter, a 50A/650V IGBT is being utilized.
- In the TNPC topology, T1 and T4 are 1200V IGBTs, while T2 and T3 are 650V IGBTs.

The 2-level three-phase inverter is often preferred due to its simple circuit topology, reduced number of power devices, and lower leakage current. However, bipolar modulation can lead to elevated voltage stress and increased switching losses. Figure 4 illustrates the thermal limitations calculated based on the diodes (D1 and D2) and transistors (T1 and T2).

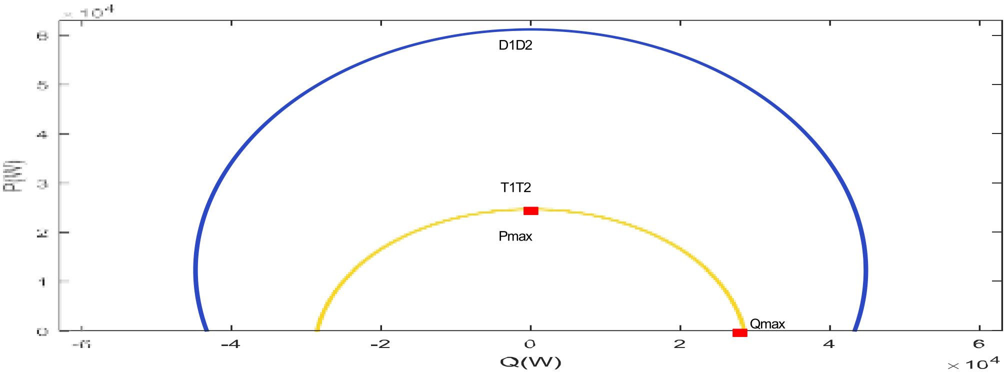
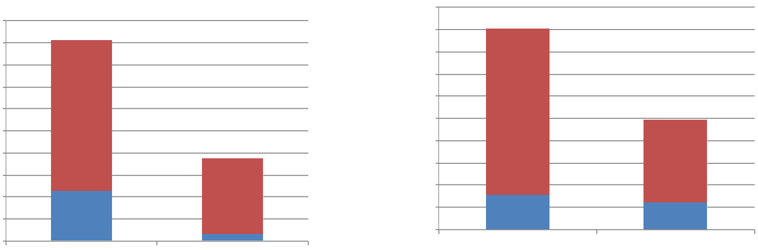


Fig.4. Full bridge thermal constraint of P and Q

The blue curve in the graph signifies a 35W loss constraint for diodes D1 and D2, whereas the yellow line represents a 44.87W loss constraint for IGBTs T1 and T2. Pmax and Qmax refer to the maximum capabilities of active and reactive power output, respectively. Fig. 5 (a) and (b) illustrate the breakdown of losses when the inverter output is at Pmax or Qmax.

In both scenarios, when the output reaches the Pmax or Qmax limits, the 44.87W constraint is specifically met in transistors T1 and T2. This suggests that the thermal bottleneck for the 2-level inverter is indeed with the IGBTs T1 and T2. Furthermore, Pmax and Qmax are almost identical due to the evenly distributed losses experienced during rectifier and inverter operations.



(a) Pmax (b) Qmax

Fig.5.The loss distributions of Pmax and Qmax

The 3-level Neutral Point Clamped (NPC) inverter is widely used in PV systems and has been extensively researched in the literature. It includes additional clamping diodes (D5, D6) and two sets of two series-connected IGBTs. It reduces leakage current and offers several advantages, such as minimized voltage stress, improved output voltage waveform, and decreased switching losses. The thermal constraints for active power (P) and reactive power (Q) in the three-phase NPC inverter are depicted in Fig. 6.

The blue curve represents a 31.81W constraint loss for diodes D5 and D6; the yellow line indicates a 40.69W constraint loss for IGBTs T1 and T4, and the green line signifies a 40.69W constraint loss for IGBTs T2 and T3.

Table II Model and Simulation of a Results Modified Constraint

Parameters	2-Level	NPC	TNPC
Number of Power device	6	18	12
Quality Output voltage	Low	high	high
Active power capability	25.2kW	67.2kW	28.5kW
Total loss for Pmax	384.8W	533.24W	330W
Loss percentage for Pmax	1.527%	0.7935%	1.158%
Reactive power capability	28.8kvar	68.7kvar	57.6kvar
Loss percentage Qmax	418.8W	476W	597.8W
Loss percentage for Q	1.4546%	0.6931%	1.038%
Reactive power constraint factor k	**1.1429**	**1.02**	**2.02**

During hours of active power generation, the PV inverter's reactive power generation leads to additional losses, reducing the total energy yield. Conversely, when the PV panels are not producing power at night, the grid must supply all losses incurred by the devices. Hence, analyzing the cost implications of generating reactive power is crucial.

Building upon earlier sections, a comparative analysis of three PV inverters is conducted, focusing on cost, output waveform quality, and power output capability, as summarized in Table II. The conclusions drawn from this analysis are as follows:

1. All three inverters exhibit more extensive capabilities for generating reactive power than active power, with the TNPC inverter demonstrating the highest ratio. Its reactive power capability is twice that of its active power capability.
2. The losses associated with generating reactive power are more minor than those incurred during active power generation.

Conclusions

When the PV inverter generates reactive power during operational hours, it incurs additional losses, ultimately reducing the total energy yield. Conversely, when the PV panels are not producing power at night, the grid must compensate for all the losses from the devices. Therefore, understanding the cost implications of generating reactive power is crucial.

Expanding on previous sections, three PV inverters are compared, focusing on cost, output waveform quality, and power output capability, as summarized in Table II. The conclusions drawn are as follows:

1. All three inverters can generate more reactive than active power, with the TNPC inverter exhibiting the highest ratio. Its reactive power capability is twice that of its active power capability.
2. The losses associated with generating reactive power are more minor than those for active power generation.

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